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Plasma physics : ion energy in RF plasma etching

J. Taillet

Office National d'Etudes et de Recherches Aérospatiales, 92320 Châtillon, France

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Résumé. — On montre que l'énergie cinétique des ions bombardant le substrat dans le procédé de gravure par plasma à haute fréquence est donnée par une expression simple en fonction de quatre paramètres caractérisant la décharge.

Abstract. — In RF plasma etching, the kinetic energy of the ions impinging upon the wafer can be easily computed from the value of four characteristic parameters of the gas discharge.

RF plasma etching is very useful for Large Scale Integration in the sense that it is a cheap, clean and reliable process giving a high spatial resolution. This last property is because RF plasma etching is anisotropic : the bottom of the groove is deepened, but its walls are not attacked, as is often the case in the wet process : smaller details can be etched, as they will not disappear by chemical erosion.

Although the analysis of the physical mechanism responsible for this anisotropy is beyond the scope of this paper, recent experiments have shown that ion bombardment, at a few hundred eV, of the bottom of the groove is an essential item ; the walls of the groove, being protected from this bombardment, are attacked much more slowly by the active etching chemical species, and the etching rate is considerably larger for the bottom than for the walls.

It has recently been demonstrated by Winters that electron bombardment of molecularly adsorbed halocarbon gases will initiate dissociative processes which cause chlorine and fluorine to be strongly bound to the surface and quickly enter into the etching reaction [1]. The same effect is anticipated from ion bombardment, which is expected to be more likely in plasma etching with a RF discharge, where the plasma potential is positive with respect to the walls. Actually, these discharges have electron temperatures of the order of a few electron volts, and it can seem paradoxical to obtain kinetic energies one order of magnitude more for the ion impinging upon the wafer. We will explain this apparent paradox in the present letter.

1. **Typical values of discharge parameters in plasma etching.** — The discharges currently in use for etching are RF capacitive discharges, for example in CF_4 or a mixture of CF_4 and O_2, at a pressure of between 0.1 and 1 mbar, and at a frequency $\omega/2\pi$ in the 1-30 MHz range. The wafer can be placed on one of the two excitation electrodes, or on a support immersed within the plasma. In this paper, the first configuration is, for the sake of simplicity, studied with a one-dimensional geometry.

In a typical case, the RF power density is 36 kW/m^3. The electron mean free path λ, deduced from the pressure p, the neutral temperature and an approximate value of the cross section of 10 Å^2, ranges from 0.3 to 3 mm : it is much larger than the groove thickness ($\simeq$ 1 μm). The electronic temperature T_e varies from 3 to 8 eV according to the nature of the gas. Its value is predicted from E/p (ratio of the electric field to the working pressure), where E is the A.C. field (approximation valid if $\omega \ll \nu$, where ν is the electron neutral collision frequency). When ν is predicted from the values of p and T_e, one finds $\nu \simeq 10^9$, which is much larger than ω [2].

The electronic density n_e is not known ; this type of discharge has not been subjected to precise measurement, maybe because of the difficulty of using Langmuir probes in the presence of RF. One can guess that this density is about 10^{16}-10^{17} m^{-3}. At any rate, this parameter is not relevant in the present calculation. The Debye radius, deduced from n_e and T_e, is about 100 μ. The sheath thickness is therefore smaller than or equal to the mean free path : these conditions permit an ion bombardment of the bottom — and only of the bottom — of the groove from the plasma boundary, which is far enough from the wafer for its shape to be unaffected by the details of the groove. The kinetic energy of the impinging

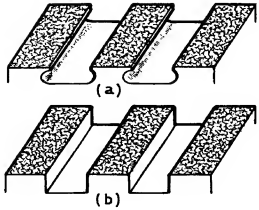

Fig. 1. — *a*) Isotropic etching. *b*) Anisotropic etching.

ions is given by the product of their charge and the plasma potential with respect to the electrode. The scope of the present paper is to show that the knowledge of this kinetic energy does not require a complete modeling of the discharge. This energy can be computed entirely from the four following parameters :

— the electronic temperature T_e,
— the plasma frequency $\omega_p/2\pi$,
— the working frequency $\omega/2\pi$,
— the energy acquired by the average electron between two collisions W_-.

From the variations of these parameters, one can deduce if the etching tends to be more or less anisotropic.

2. **A general property of the plasma potential for capacitive RF discharges.** — Capacitive RF discharges are sustained by the A.C. current which traverses the sheaths located between plasma and electrodes. This current imposes a RF voltage v_A across the sheath, and, if the frequency is low enough and the power high enough, its RMS value V_A is much higher than the plasma potential due to ambipolar diffusion in the D.C. discharge at the same electronic temperature. In the case considered here, an electron crosses the sheath in a time very short compared to the period

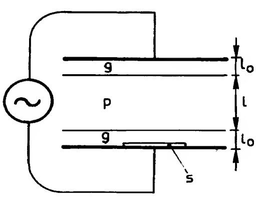

Fig. 2. — Discharge geometry. s : wafer ; p : plasma ; g : sheath.

($\omega \ll \omega_p$). This shows that if, at a given time, the voltage v_A across the sheath is such that the plasma potential is negative with respect to the electrode, electrons will be lost instantly up to the point where the plasma is positive : this mechanism imposes a positive D.C. potential V_p to the plasma, such that V_p is greater than the peak value $V_A\sqrt{2}$ of the A.C. voltage applied to the sheath. This rectification effect (similar to the behaviour of a diode) determines the energy of the ions impinging on the wafer placed upon the electrode. Note that, as the plasma potential adjusts itself to a value such that the electronic and ionic currents leaving the plasma are equal, an insulating wafer has the same surface potential as the supporting electrode.

In the following computation, the effects of the electronic temperature on the D.C. plasma potential will be neglected, and the formula :

$$V_p = V_A\sqrt{2}$$

will be adopted.

3. **Relationship between discharge parameters and plasma potential.** — The A.C. voltage across the sheath is : $V_A = iC_0^{-1}\omega^{-1}$ with $C_0 = \varepsilon_0 S l_0^{-1}$ and $i = (P/R)^{1/2}$ where i is the A.C. current injected by the RF generator, C_0 the sheath capacity, S its area, l_0 its thickness, P the absorbed power, R the plasma resistance, ε_0 the permittivity of free space. Consequently :

$$l_0 = \varepsilon_0 S\omega V_A(P/R)^{-1/2} . \tag{1}$$

The sheath thickness is given by Child's law :

$$l_0 = \frac{2}{3}\varepsilon_0^{1/2} n_e^{-1/2} \frac{2^{1/4}}{e^{1/4}} \frac{1}{(kT_e)^{1/4}} V_p^{3/4} \tag{2}$$

where n_e is the electronic density, T_e the electronic temperature, V_p the D.C. voltage across the sheath, k the Boltzmann constant, and e the electron charge.

If the relationship $V_p = V_A\sqrt{2}$ is introduced, elimination of l_0 between (1) and (2) gives :

$$eV_p . kT_e = (2\sqrt{2})^2 \left(\frac{2}{3}\right)^4 \left(\frac{P}{R}\right)^2 \varepsilon_0^{-2} n_e^{-2} S^{-4} \omega^{-4} . \tag{3}$$

The plasma resistance is

$$R = mvln_e^{-1} e^{-2} S^{-1} \tag{4}$$

where m is the electron mass and l the plasma thickness.

Let $W_+ = eV_p$ be the potential energy of the plasma ions (if the ions having unit charge are considered), and

$$W_- = Pl^{-1} S^{-1} n_e^{-1} \nu^{-1} \tag{5}$$

the energy acquired by the average electron between two collisions. One gets :

$$\sqrt{kT_e \cdot W_+} = 1.26\left(\frac{\omega_p}{\omega}\right)^2 W_- . \qquad (6)$$

The following rule can be formulated :

The geometric mean of the thermal energy of the electrons and the potential energy of the plasma ions is approximately equal to the product of the energy acquired by the average electron between two collisions and of the square of the ratio of the plasma frequency to the working frequency.

This rule shows, all other parameters being kept constant, that the ion potential energy varies inversely with the fourth power of the working frequency. If the mean free path of the ions λ_i is greater than the sheath thickness, the potential energy of the ions is converted into kinetic energy for the ions impinging upon the wafer. In this case, for a given mixture, the best etching is obtained for the lowest frequency. This prediction agrees with the experimental results [3].

The formula (6) is very useful in conjunction with the inequality $l_0 \leqslant \lambda_i$ with

$$l_0 = (W_-)^{3/2} . (kT_e)^{-1} . \omega_p^2 . \omega^{-3} \, m^{-1/2} \qquad (7)$$

to determine if the conditions allowing an energetic and anisotropic ion bombardment of the wafer are met for a given set of parameters.

4. Value of the parameters in a typical case. — For a discharge in CF_4 or $CF_4 + O_2$:

$$\omega = 2\pi \times 13.56 \text{ MHz} ; \quad l = 0.04 \text{ m} ; \quad S = 0.126 \text{ m}^2 ;$$
$$P = 20 \text{ W} ; \quad T_e = 8 \text{ eV} ; \quad p = 0.1 \text{ torr} ;$$
$$n_e = 4 \times 10^{16} \text{ m}^{-3} ; \quad \nu = 0.5 \times 10^9 ;$$
$$\lambda = 3 \times 10^{-3} \text{ m} ; \quad \lambda_i \simeq 7 \times 10^{-4} \text{ m} ;$$
$$R = 0.1 \, \Omega ; \quad i = 15 \text{ A} ; \quad l_0 = 5 \times 10^{-4} \text{ m} ;$$
$$W_- = 1.25 \times 10^{-3} \text{ eV} ; \quad \left(\frac{\omega_p}{\omega}\right)^2 = 1.75 \times 10^4 ;$$
$$V_p = V_A \sqrt{2} = 100 \text{ V} .$$

This example shows that the A.C. voltage of the generator is used mainly to force the current through the sheath ; the A.C. voltage drop in the plasma is only a few volts. The high D.C. potential of the plasma generates an important ionic bombardment of the bottom of the groove, and improves etching anisotropy.

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